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Geophysics

Neodymium isotopes in flood basalts from the Siberian Platform and inferences about their mantle sources

(strontium isotopes/trace elements/igneous petrology/earth evolution)

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ABSTRACT **The initial isotopic compositions of Nd and Sr in basalts from the Central Siberian Plateau and other major continental flood basalts are reported. The continental flood basalts appear to be the product of partial melting of mantle sources that consist of relatively primitive undifferentiated material and are clearly distinct from midocean ridge basalts, which sample mantle reservoirs that have been modified by extraction of continental crust earlier in earth history. These observations provide fundamental constraints on models of mantle structure and dynamics. Isotopic effects of crustal contamination are clearly recognizable in some continental flood basalts, but these effects can be distinguished from isotopic patterns inherited from the mantle magma sources.**

The purpose of this work is to exhibit data on the isotopic composition of Nd in continental flood basalts (CFBs) that appear to confirm the isotopic contrasts between these magmas and oceanic ridge basalts inferred by DePaolo and Wasserburg (1, 2). In addition, we discuss some of the consequences of this distinction for the structure and history of the earth's mantle. Studies of basalts have been a matter of continued geologic interest because the lavas are presumed to represent the underlying mantle. An extensive discussion of basalt genesis and its relation to earth structure, emphasizing petrologic arguments, is given in ref. 3. In the present study, isotopic and trace element variations are emphasized.

The largest CFB provinces have ages less than ≈0.25 aeon (1 aeon = 10^9 years), which is similar to the maximum age of the ocean basins (≈0.2 aeon). Thus, the lavas considered here provide a comparison of continental and oceanic volcanism over a time span that is short compared to the age of the earth. In general, the major element chemical compositions of continental and oceanic basalts are similar. Trace element abundances show midocean ridge basalts (MORBs) are depleted in so-called "large ion lithophile" or "incompatible" elements relative to CFBs (4). MORBs were inferred to come from relatively primitive sources (5), until Tatsumoto *et al.* (6) and Gast (7) called attention to the depleted trace element patterns and suggested that these reflected the differentiated character of the mantle magma sources. Trace-element and isotopic distinctions between MORBs and intraplate oceanic island basalts (e.g., Hawaii) have been amply documented (6, 8). However, the distinction between MORBs and CFBs has received relatively little attention. The possibility of crustal contamination in continental volcanics has to some extent limited the interest in these rocks as samples of mantle sources (9).

Distinctions in the modes of emplacement of these two basalt types may relate to differences in their mantle sources. CFBs are erupted from extensive fissure systems. High rates of eruption and low viscosity allow the lavas to flow long distances and result in the "flooding" of large areas. In contrast, MORBs tend to be erupted more passively onto the ocean floor, and appear in general to fill fissures at mid-ocean ridges, where they are rapidly quenched. By sequential displacement through seafloor spreading, MORBs cover the entire floor of the oceans. Both basalt types also occur as sills. CFBs are erupted through relatively thick sections of low-density continental crust and therefore require a substantial hydrostatic head. MORBs, on the other hand, are erupted at low topographic levels where there is essentially no crust and therefore require ≈1 kilobar (10^8 Pa) smaller hydrostatic head.

In previous studies of variations in the $^{143}Nd/^{144}Nd$ ratio (1, 2, 10), it was shown that CFBs typically have ϵ_{Nd} (excess of $^{143}Nd/^{144}Nd$ in parts in 10^4 relative to a model bulk earth standard) in the neighborhood of 0, whereas oceanic flood basalts have ϵ_{Nd} of about +10. The data base CFBs upon which this generalization rested was limited. To test this rule we analyzed basalt samples from the Central Siberian Platform. In this region basaltic lavas (flows, dikes, sills, and plugs) flooded more than 10^6 km^2 during Triassic time and reached thicknesses of up to 2 km. These rocks, called the "Siberian Traps," are associated with other contemporaneous volcanic piles which together compose one of the most extensive manifestations of continental volcanism in the world. This CFB province is particularly interesting because it is located far from the present continental margins on a large cratonic block that has been stable throughout most of the Phanerozoic epoch. In addition to the study of Siberian Platform samples, we also report data from two other CFB provinces, the Parana Basin of southern Brazil and the Columbia River province of the northwestern United States. These provinces differ somewhat from the Siberian Traps in that they are located fairly close to continental margins. The eruption of the Parana basalts has been associated with the opening of the South Atlantic Ocean and is roughly time-correlative with eruption of the Karroo basalts of South Africa (11). The Columbia River province, however, occupies a different type of tectonic position, being on the continental side of an andesitic volcanic arc (the Cascades) that has been associated with an inferred subduction zone along the western margin of North America (12). However, all three of these basalt occurrences share the physical characteristics discussed above. The chemical composition of the lavas in all three are classified as "tholeiitic" (13). The Columbia River basalts appear to be somewhat more evolved than the others, because they are relatively enriched in SiO_2 and K_2O, and depleted in MgO.

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Abbreviations: CFB, continental flood basalt; MORB, midocean ridge basalt.

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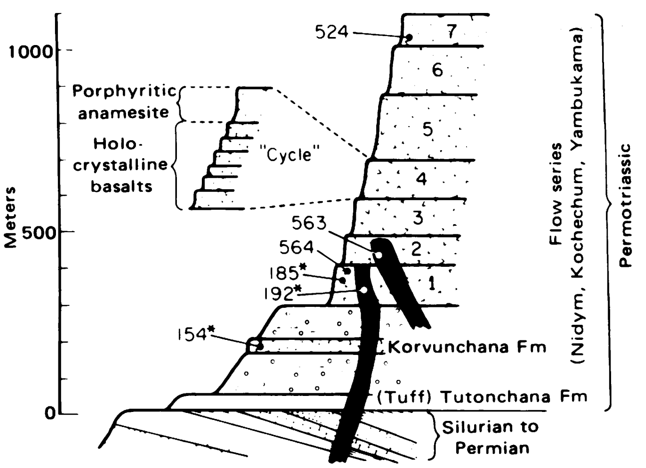

FIG. 1. Idealized partial stratigraphic section of East Siberian Traps, Tunguska Basin, Siberian Soviet Socialist Republic, showing stratigraphic locations of basalt and diabase samples analyzed in the present study. Sample numbers with asterisks are from a different locality than the others. Fm, formation.

SAMPLES

Through the interest of Director V. L. Barsukov of the Vernadsky Institute and the courteous aid of Dr. Yuri I. Dmitriyev, a suite of six samples from the Siberian Traps was provided to us. General descriptions of the Traps may be found in refs. 14 and 15, and the petrochemistry in the areas of the sample localities is discussed in refs. 16–18. The Siberian basalts analyzed are from the central Tunguska Basin. An idealized stratigraphic section is shown in Fig. 1, constructed from descriptions by Dmitriyev (16, 17). The volcanic rocks rest unconformably on Silurian to Permian sediments. The lowermost volcanic unit, the Tutonchana Suite, consists of tuffs and tuffaceous sands and silts. This is overlain by the Korvunchana Suite, which consists mainly of large-fragmental and lapilli tuffs that contain xenoliths of both the Paleozoic basement rocks and tholeiitic basalts and diabases similar to the overlying rocks. The flows are subdivided into the Nidym, Kochechum, and Yambukana series primarily on the nature and amount of interlayered sedimentary rocks (not shown in Fig. 1). The 800-m-thick flow series is described (16) as consisting of seven "cycles," each of which contains five to six holocrystalline basalt flows capped by a thicker flow described as "porphyritic anamesite." Fig. 1 also shows the stratigraphic position of the samples analyzed. The asterisks indicate samples from the southern limb of the Tunguska synclinorium, whereas the other samples are from the central part of the basin. This small suite of samples contains representatives of both the bottom and top of the section and of intrusive and extrusive units. Samples ES-185 and ES-564 provide a sampling from similar stratigraphic levels at two different locations. Many of the sills and dikes exhibit evidence for assimilation of older sedimentary rocks (partially digested xenoliths) (18). Further evidence of contamination is provided by the observation that quartz-bearing diabases are restricted to dikes and sills intruding quartz-rich arenites. K–Ar ages on whole rocks have been reported on similar samples; the ages range from 0.278 to 0.170 aeon, but cluster at 0.240–0.250 aeon (18).

The Siberian samples are composed primarily of plagioclase and augite with subordinate amounts of opaque oxides. All samples except ES-185 contain up to a few percent modal olivine. Postcrystallization alteration is minimal in all samples. The samples are listed in Table 1 along with the concentrations of K, Ba, Rb, Sr, Nd, and Sm. It can be seen that they show a wide range in concentration of the alkalis, but have distinctly low K content in comparison with alkali basalts which average ≈12,500 ppm K (19). Note that the Rb/Sr ratio varies by more than a factor of 100 whereas Sm/Nd shows only 10% variation. The Sm/Nd ratios are uniformly about 10–15% lower than chondritic, whereas Rb/Sr ranges from much lower to much higher than the nominal "bulk earth" value of 0.029 (2). Sr and Nd contents are consistently about 15–20 times chondritic, and the Sr/Nd weight ratio is generally slightly lower than the chondritic value of ≈18.

Also shown in Table 1 are data on flood basalts from the Columbia River province of Washington and Oregon and the Parana Basin of southern Brazil. Three samples of Lower Yakima basalt from the Columbia River province have been analyzed. The Lower Yakima basalts are known to exhibit chemical uniformity over extensive areas and make up most (≈80%) of the volume of the Columbia River basalts (20). Sample DTY-18 is from the section exposed at Tygh Ridge (21). DSG-2 is from Sentinel Gap, Washington, and DSTW 73-355 is from southeastern Washington (T14N, R40W). In contrast to these samples we have also analyzed a sample of Upper Yakima basalt (DSTW 73-22) from Devil's Canyon, Washington. The Upper Yakima basalts consist of a wide variety of chemical types but are of small volume compared to the Lower Yakima sequence (20). The samples analyzed in this study, taken in conjunction with previously measured samples of Picture Gorge basalt (2) and Lower Yakima basalt BCR-1 (1)

Table 1. Trace element contents and element ratios*

Sample	K	Ba	Rb	Sr	Sm	Nd	Rb/Sr	Sm/Nd	K/Rb	Sr/Nd
Siberian basalts										
ES-192	2,220	—	7.81	189	3.5	12.2	0.041	0.284	284	15.5
ES-564	1,520	—	10.7	185	3.4	11.6	0.058	0.291	142	15.9
ES-563	2,414	150	2.69	212	3.5	12.7	0.013	0.278	897	16.7
ES-154	6,240	—	20.9	198	4.2	15.8	0.106	0.263	299	12.5
ES-185	778	—	0.135	173	2.9	9.97	0.0008	0.293	5763	17.4
ES-524	1,190	64	3.64	165	3.3	11.4	0.022	0.293	327	14.5
Columbia River basalts										
DSG-2	9,000	—	26.7	320	5.6	23.3	0.083	0.240	337	13.7
DSTW 73-355	5,610	—	16.3	377	4.4	19.2	0.043	0.229	344	19.6
DSTW 73-22	14,600	—	53.0	271	8.5	39.3	0.196	0.216	275	6.9
Parana basalts										
PAR-1	15,200	277	36.4	679	7.82	46.1	0.0536	0.170	418	14.7
PAR-2	8,800	317	23.3	353	6.13	27.7	0.0660	0.221	378	12.7

* All concentrations are in ppm by weight; precision is approximately ±1–2%.

Table 2. Isotopic compositions of CFBs

Sample	$f_{Sm/Nd}$*	$f_{Rb/Sr}$†	$^{143}Nd/^{144}Nd$‡	$^{87}Sr/^{86}Sr$§	$\epsilon_{Nd}(T)$‖	$\epsilon_{Sr}(T)$
Siberian basalts (T = 0.23 aeon)						
ES-192	−0.112	+0.430	0.511878 ± 16	0.70496 ± 3	+1.4 ± 0.4	+4.9 ± 0.7
ES-564	−0.091	+1.00	0.511853 ± 24	0.70520 ± 3	+0.8 ± 0.5	+6.1 ± 0.8
ES-563	−0.132	−0.559	0.511821 ± 25	0.70534 ± 3	+0.5 ± 0.6	+14.1 ± 0.6
ES-154	−0.179	+2.65	0.511835 ± 30	0.70606 ± 3	+1.0 ± 0.7	+11.9 ± 1.4
ES-185	−0.086	−0.973	0.511936 ± 23	0.70487 ± 4	+2.4 ± 0.5	+8.9 ± 0.9
ES-524	−0.086	−0.237	0.511985 ± 21	0.70470 ± 4	+3.4 ± 0.5	+3.8 ± 0.7
Columbia River basalts (T = 0.01 aeon)						
DTY-18	—	—	0.511885 ± 28	0.70502 ± 5	+1.0 ± 0.5	+7.4 ± 0.8
DSG-2	−0.246	+1.87	0.511854 ± 21	0.70526 ± 4	+0.4 ± 0.4	+10.5 ± 0.5
DSTW 73-355	−0.287	+0.490	0.511882 ± 22	0.70500 ± 4	+0.9 ± 0.4	+7.0 ± 0.6
DSTW 73-22	−0.329	+5.327	0.511262 ± 21	0.71476 ± 3	−11.2 ± 0.4	+145 ± 1
Parana basalts (T = 0.12 aeon)						
PAR-1	−0.469	+0.848	0.511688 ± 20	0.70508 ± 11	−1.5 ± 0.4	+6.6 ± 2.0
PAR-2	−0.310	+1.276	0.511577 ± 26	0.70579 ± 5	−4.2 ± 0.5	+15.7 ± 0.7

See refs. 1 and 10 for complete list of equations and numerical parameters for Nd and analogous equations for Sr.

* $f_{Sm/Nd} \equiv (^{147}Sm/^{144}Nd)_{Sample}/(^{147}Sm/^{144}Nd)_{CHUR} - 1$; $(^{147}Sm/^{144}Nd)_{CHUR} = 0.1936$.

† $f_{Rb/Sr} \equiv (^{87}Rb/^{86}Sr)_{Sample}/(^{87}Rb/^{86}Sr)_{UR} - 1$; $(^{87}Rb/^{86}Sr)_{UR} = 0.0839$.

‡ Measured value, normalized to $^{150}Nd/^{142}Nd = 0.2096$; uncertainties are $\pm 2\sigma$.

§ Measured value, normalized to $^{86}Sr/^{88}Sr = 0.1194$; uncertainties are $\pm 2\sigma$.

‖ $\epsilon_{Nd}(T) \approx \epsilon_{Nd}(0) - f_{Sm/Nd}Q_{Nd}T$, in which $Q_{Nd} = 24.7$, age T in aeons. $\epsilon_{Nd}(0) = [(^{143}Nd/^{144}Nd)_{Sample}/(^{143}Nd/^{144}Nd)_{CHUR} - 1] \times 10^4$; $(^{143}Nd/^{144}Nd)_{CHUR} = 0.511836$.

cover a wide stratigraphic and areal range and can be considered fairly representative of the Columbia River basalts. Both the Picture Gorge and the Upper Yakima samples were chosen because they exhibit peculiarities in Sr isotopic composition relative to the bulk of the lavas in the province (22). The Columbia River samples have abundances of alkalies, Sr, Sm, and Nd that are significantly higher than in the Siberian basalts.

Samples PAR-1 and PAR-2 are Parana basalts that were provided by Dr. Umberto Cordani of the University of Sao Paulo, Brazil. Both samples are from a drill core near Santa Catarina (49° 55′ W, 28° 46′ S) and have K-Ar ages of 0.120 aeon (23). PAR-1 is from the base of the section (elevation 300 m) and PAR-2 is from higher in the section (elevation 750 m). The major element compositions of Parana basalts are discussed

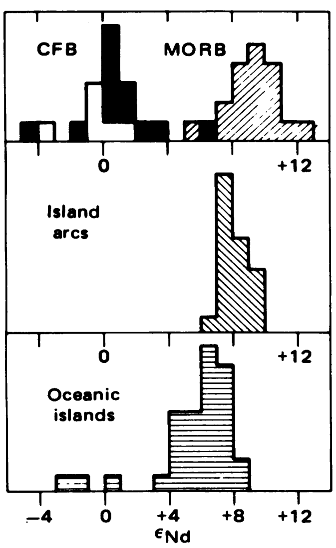

FIG. 2. Histogram showing initial ϵ_{Nd} values for young (<0.25 aeon) CFBs, MORBs, island arcs, and oceanic island basalts. Solid blocks represent CFB samples measured in the present work. The contrast between CFBs and MORBs is clearly shown. Data are from refs. 1, 2, 10, and 26–28. Sample DSTW 73-22 is not shown.

in refs. 24 and 11. It is unknown whether samples analyzed in the present work are representative of this province. The trace element concentrations in the analyzed samples suggest affinities with alkali basalts, and may indicate that they are not representative.

RESULTS

The analytical procedures used have been described (1, 25) and the data representations are from refs. 1, 2, and 10. The isotopic compositions of Nd and Sr for the samples analyzed are presented in Table 2 along with the deviations of the initial values of $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ from those evolved in a chondritic uniform reservoir (CHUR) and a uniform reservoir (UR) respectively. The Siberian samples have ϵ_{Nd} with a total range from +0.5 to +3.4. The Sr isotopic composition is more variable, ranging from $\epsilon_{Sr} = +3.8$ to $\epsilon_{Sr} = +14.1$. Data on the Lower Yakima basalts from the Columbia River province all lie in a narrow range from $\epsilon_{Nd} = +0.4$ to $+1.0$ and $\epsilon_{Sr} = +7$ to $+11$. The Upper Yakima basalt sample, however, has an isotopic composition that is drastically different ($\epsilon_{Nd} = -11.2$, $\epsilon_{Sr} = +145$). The Parana samples have small negative values of ϵ_{Nd} and positive values of ϵ_{Sr}. The Nd data are displayed in a histogram (Fig. 2) along with all of the previously published results on Phanerozoic CFBs and MORBs (1, 2, 10, 26–28). The new data from the Siberian Traps and the typical samples of the Columbia River fall at the peak of the histogram based on previous studies and strongly emphasize the differences between continental and oceanic flood basalts. The Picture Gorge basalt, chosen because it exhibits similarities with oceanic basalts (particularly $^{87}Sr/^{86}Sr$), has ϵ_{Nd} ($\approx$+6), which confirms these similarities. Thus, the Picture Gorge sequence, confined to the extreme southern part of the Columbia River province, provides evidence that oceanic-type mantle may extend beneath the continents in an irregular fashion in this region. Also shown on Fig. 2 are data for island arcs (Marianas, New Britain, South Sandwich Islands), which show clear affinities in ϵ_{Nd} with the MORB basalts. The ocean islands samples and some continental alkali basalts show intermediate values (29, 30).

The Upper Yakima basalt sample DSTW 73-22 is far displaced from $\epsilon_{Nd} = 0$, and also has an anomalous value of ϵ_{Sr}.

These effects, and also certain trace element characteristics (high Rb and Rb/Sr, low Sr/Nd) strongly suggest that the isotopic composition of this lava was modified by contamination from crustal rocks. Similar Nd isotopic effects have been found previously in other flood basalts (2, 10, 30). For all these samples, the observed Nd and Sr isotopic effects are precisely those expected on theoretical grounds for contamination of young basalt magma with old upper crustal material (31). Crustal contamination has also been previously recognized for Pb and Sr in a variety of continental igneous rocks (32–35).

The data on sample DSTW 73-22 are particularly interesting in that they require a crustal contaminant of great age (probably ≳2.5 aeons). No crystalline basement rocks of such great age are known in the immediate area of the central Columbia River Basin. However, such old rocks are found to the east in Idaho and Montana. This datum therefore requires that either (*i*) Precambrian crystalline basement underlies central-southern Washington, or (*ii*) younger continental sediments whose provenance lies in the crystalline terrain to the east acted as the contaminant. A substantial fraction (≈50%) of the trace elements in this rock must have come from the ancient crust. This observation is important with regard to the age and structure of the continental crust in this area (cf. ref. 36). The approach used here may be of general utility in identifying the existence of ancient continental crust where it is covered by younger formations.

The Nd and Sr isotopic data on samples that show no obvious evidence for large amounts of crustal contamination are displayed on an ϵ_{Nd}–ϵ_{Sr} diagram in Fig. 3. Also shown is the so-called "mantle correlation line" (2, 27), which is best defined by oceanic samples. The Siberian samples lie in the neighborhood of $\epsilon_{Nd} = 0$, $\epsilon_{Sr} = 0$ but are clearly displaced toward higher ϵ_{Sr} and ϵ_{Nd}. The Lower Yakima basalt samples have ϵ_{Nd} and ϵ_{Sr} values that are closely similar to those of the Siberian basalts. The Upper Yakima sample, not shown on Fig. 3, would lie far off to the right on this diagram. The data points from the Parana basalts generally lie in the neighborhood of the correlation line. These and some previous data show a distinct tendency to lie on the extension of the line below the origin. If more extensive data on CFBs basalts should demonstrate that many have Nd and Sr isotopic parameters substantially below $\epsilon_{Nd} = \epsilon_{Sr} = 0$

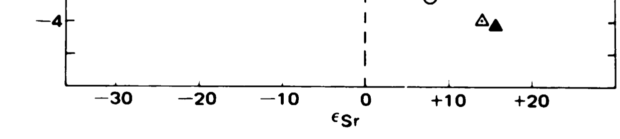

FIG. 3. ϵ_{Sr}–ϵ_{Nd} diagram showing data for CFBs (▲,△) and oceanic basalts. The data from the present study are shown in filled symbols. Other data are from refs. 1, 2, 10, and 26–28. The heavy diagonal line is the correlation line defined by midocean ridge (⊡) and oceanic island (⊙) basalts (2, 10, 27). The Siberian and Columbia River samples lie in the neighborhood of the line but are distinctly displaced to the right by 10 units in ϵ_{Sr}. Two of the data points also have significantly high ϵ_{Nd}. The two Parana samples lie near the extension of the correlation line.

which cannot be attributed to contamination, then it may be necessary to revise estimates (10, 27) for the values of Sm/Nd and Rb/Sr in the bulk earth.

The data points shown on Fig. 3 that lie on or near the trend of the mantle correlation line are interpreted to be representative of mantle magma sources. The MORB data can be seen to cluster at the high-ϵ_{Nd}, low-ϵ_{Sr} extreme of the trend. The small but significant displacement of the CFB data away from the correlation line toward positive ϵ_{Sr} is interpreted to be the result of modest amounts of crustal contamination. For the Columbia River basalts we can estimate the ϵ_{Nd} prior to contamination by using the data on sample DSTW 73-22, which is dominated by contamination, to determine the slope of the displacement vector on the ϵ_{Nd}–ϵ_{Sr} plot. Correction of the other Columbia River samples back to the correlation line in this manner requires an increase in ϵ_{Nd} of 0.5 to 1.0 units. A similar correction for the Siberian samples would require an increase of about 1 ϵ unit for all samples. Therefore, contamination corrections would move the CFB peak of the histogram in Fig. 2 to the right by one unit to an ϵ_{Nd} of about +1 to +2. Thus, after allowance for contamination, the CFBs are still clearly distinguished from the MORBs.

CONCLUSIONS AND IMPLICATIONS

We conclude, therefore, that the expanded sampling of CFB provinces provided by the present study bears out the previous conclusion (2) that a consistent isotopic contrast exists between MORBs and CFBs. This observation requires the existence of two widespread mantle reservoirs that have been mutually isolated for more than ≈1 aeon. Furthermore, the pronounced clustering of the CFB data near $\epsilon_{Nd} = 0$ suggests that these lavas are being derived from previously undifferentiated regions of the mantle.

Any acceptable model of the structure and dynamics of the earth's mantle and their development through earth history must account for the regular isotopic differences reported here. The simplest model, which may also be consistent with petrologic considerations and plate tectonics, would be a two-layer mantle. The shallow mantle, with $\epsilon_{Nd} \approx +10$ and $\epsilon_{Sr} \approx -30$, would be the source of MORBs. The deep mantle would be essentially undifferentiated primary material, have $\epsilon_{Nd} \approx \epsilon_{Sr} \approx 0$ and provide the source of CFBs. Other basalt types—ocean islands and island arcs—would be interpreted as derivatives from mixtures of the deep and shallow sources. The details of this model will be pursued in a separate paper. We note, however, that the MORB source, with positive ϵ_{Nd}, can be interpreted as complementary to the continental crust, which is old and has negative ϵ_{Nd} today.

The inference that continental flood basalts and, in part, oceanic basalts, are derived from previously undifferentiated deep mantle sources is a surprising conclusion. It may be reasonable to extend this inference to many Archean igneous rocks that also have $\epsilon_{Nd} \approx 0$, including silicic rocks (1, 2).

If the earth is still differentiating relatively unfractionated material, one should expect other supportive evidence. The most relevant observations in this regard are (*i*) the presence of $^{129}Xe^*$ (^{129}Xe excesses from ^{129}I decay) in some natural gases and rocks (37, 38) and (*ii*) high $^{3}He/^{4}He$ ratios (39–42) in ocean water and some igneous rocks. These observations indicate that the current flux of volatile elements contains a component that may be present only in primary juvenile materials that have never been completely outgassed. When these observations were first made, they were difficult to accept because of the then current conviction that the earth's interior was rather thoroughly outgassed of primary juvenile elements. The observations of $^{129}Xe^*$ and ^{3}He do not necessarily refute this, because it is possible that the remaining primary juvenile volatile materials represent only a small fraction of the total volatile budget and that the remaining bulk juvenile material is mostly outgassed. The model presented here for Nd requires that large ion lithophile elements, which are enriched in the earth's crust and would be expected to be depleted in any differentiated parts of the mantle, are essentially undepleted in the lower mantle. It is not evident that the outgassing efficiency should be equal to the transport of nonvolatiles, and we consider the two classes of observations to be qualitatively consistent.

In addition to independent evidence for the ongoing differentiation of relatively unfractionated material, there should also be a direct correlation between the different observations. From the models discussed here and in ref. 2, we would conclude that the magmas with $\epsilon_{Nd} = 0$ are derived from undifferentiated source material and hence the highest concentration of primary juvenile gases should be contained in these magmas at depth. Outgassing of the magmas during emplacement would alter the concentrations, but the ratio of $^3He/^4He$ and $^{129}Xe^*/^{130}Xe$ should still reflect the sources (with due consideration of U–Th decay). Primary juvenile gases should be enhanced in ocean island volcanics, but less than in continental volcanics, and the lowest enhancement should be in MORBs. Such a relationship is suggested by the recent observations of Craig and Lupton (43), who show that the high ratios of $^3He/^4He$ observed in Yellowstone (purely continental) and in Kilauea (ocean island) are greater than those found at midocean rises and conclude that the high ratios are due to deep mantle plumes. The known presence of ^3He excesses in sea water and oceanic flood basalts (39, 43) indicates juvenile additions of volatile compounds and presumably some corresponding juvenile magmatic contributions into the oceanic regions. This implies that there must be some mixing between the "depleted" mantle represented by MORBs and the undifferentiated (lower) mantle, so that the Nd and Sr in MORBs should have some contribution from the primitive source. The interpretation of the ϵ_{Nd}–ϵ_{Sr} correlation line as a two-component mixing line is fully compatible with this viewpoint (31). A more quantitative comparison should be forthcoming, although there must be obvious difficulties in comparing fugitive components with refractory elements. This is made more complex by the possible reinjection of crustal, atmospheric, and hydrospheric constituents (including H_2O, Ne, Kr, and Xe) into the oceanic mantle in the subduction process and the subsequent release of these constituents during melting (44).

We thank V. L. Barsukov, Director of the Vernadsky Institute, and Dr. Yuri I. Dmitriyev of the Institute of Geology of Ore Deposits for their generous aid in obtaining samples of the Siberian Traps and providing information on their occurrence. We are indebted to Dr. Umberto Cordani of the University of Sao Paulo, Brazil, for samples of Parana basalts and to Tom Wright and Donald Swanson of the U.S. Geological Survey for samples of Columbia River basalt and unpublished Sr data on sample 73-22, which prompted our analysis of this sample. Discussions with Donald Swanson were also of great aid. Wes Myers of Atlantic Richfield Hanford Company was very helpful in selecting Columbia River basalts, both in the field and the *cold* storage sheds. English translations of Russian articles describing the petrology of the Siberian basalts are available upon request from G.J.W. This work was supported by grants from the National Aeronautics and Space Administration (NGL 05-002-188) and the National Science Foundation (EAR 76-22494 and EAR 78-12966). This is contribution number 3196 (289) from the Division of Geological and Planetary Sciences.

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